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Comparative Assessment of Five Potential Sites for Hydrothermal-Magma Systems: Energy Transport

MASTER

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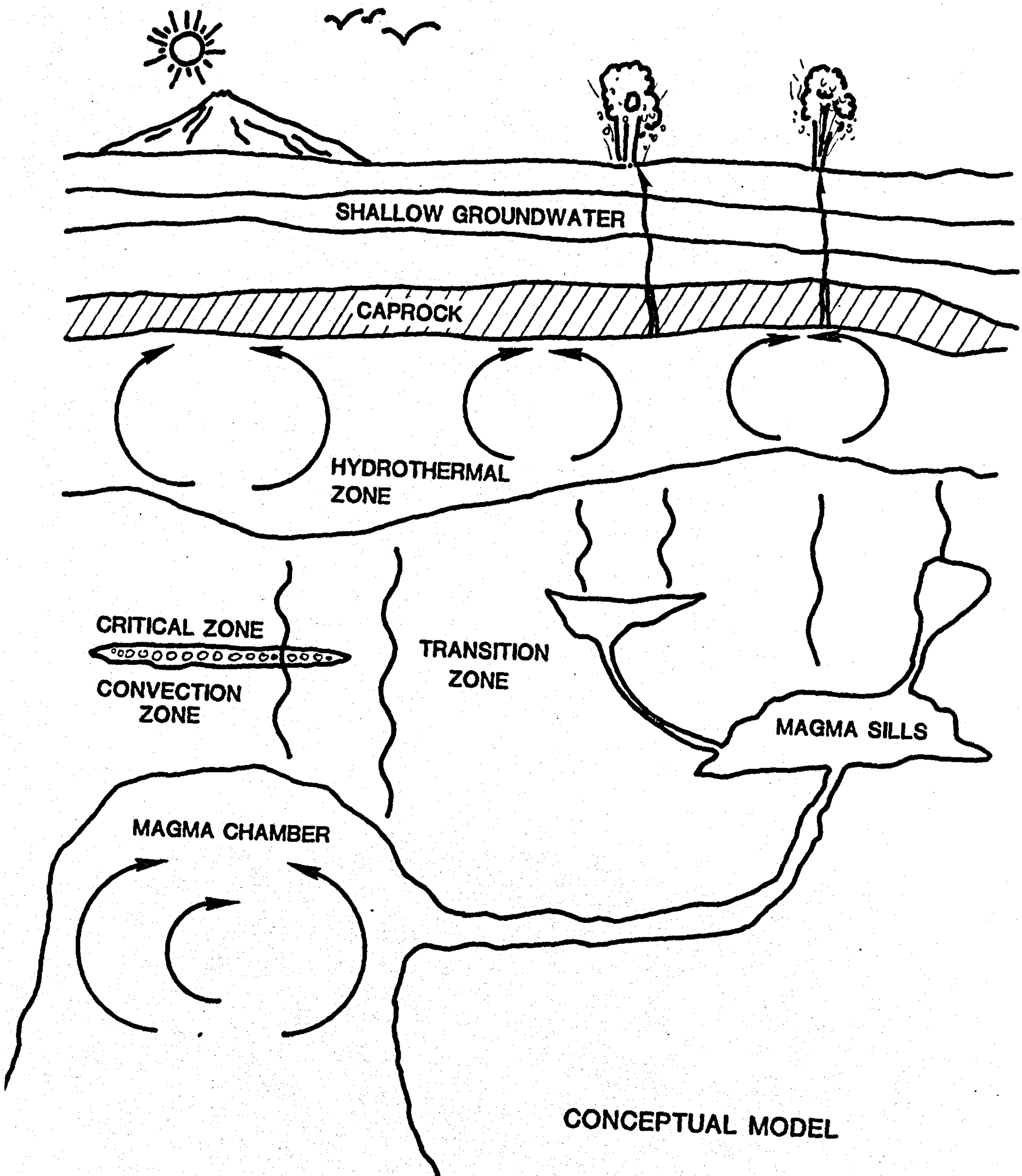
ABSTRACT

A comparative assessment of five sites is being prepared as part of a Continental Scientific Drilling Program (CSDP) review of thermal regimes for the purpose of scoping areas for future research and drilling activities. This background report: discusses the various energy transport processes likely to be encountered in a hydrothermal-magma system, reviews related literature, discusses research and field data needs, and reviews the sites from an energy transport viewpoint.

At least three major zones exist in the magma-hydrothermal transport system: the magma zone, the hydrothermal zone, and the transition zone between the two. Major energy transport questions relate to the nature and existence of these zones and their evolution with time. Additional energy transport questions are concerned with the possible existence of critical state and super-critical state permeable convection in deep geothermal systems.

A review of thermal transport models emphasizes the fact that present transport models and computational techniques far outweigh the scarcity and quality of deep field data. This points out the need for a Continental Scientific Drilling Program which can begin to generate field data from deep holes. Interpretation of future field data, however, will require the use of many of the models that the data are designed to verify.

*A part of the DOE/OBES Geosciences Continental Scientific Drilling Program.



CONCEPTUAL MODEL

Comparative Assessment of Five Potential Sites for Hydrothermal-Magma Systems: Energy Transport

Introduction

A joint proposal to conduct a comparative assessment of five potential hydrothermal-magma sites was prepared and submitted to the Department of Energy's Office of Basic Energy Sciences, Geoscience Program in November of 1979. The four DOE Laboratories involved were: Los Alamos National Scientific Laboratory, Lawrence Berkeley Laboratory, Lawrence Livermore National Laboratory and Sandia National Laboratories. The five sites were: Geysers-Clear Lake, CA., Long Valley, CA., the Salton Trough, CA., Roosevelt Hot Springs, UT., and the Rio Grande Rift, NM.

The need for a comparative assessment of the potential sites was a logical consequence of the Workshop on Continental Drilling for Scientific Purposes held at Los Alamos, New Mexico, July 17-21, 1978. This workshop resulted in a National Academy of Sciences report entitled "Continental Scientific Drilling Program", (CSDP Report, 1979). The workshop and report identified major scientific objectives in four areas: Basement Structures and Deep Continental Basins; Thermal Regimes; Mineral Resources; and Earthquakes. The Department of Energy has a particular interest in thermal regimes because of its relation to utilization of energy resources and waste disposal. Utilization of geothermal energy and disposal of geothermal fluids are obvious examples and in-situ fossil fuel utilization and nuclear waste disposal are also examples of problems where a knowledge of thermal regimes in the geologic environment is important.

A report (Comparative Assessment of Five Potential Sites for Hydrothermal-Magma Systems: Summary, Luth, and Hardee, 1980) which discusses: the five sites, important scientific questions to be resolved by drilling, and recommended future research, is being prepared jointly by the four DOE laboratories. In addition, each laboratory is jointly preparing a detailed background report which covers the sites from a dicipline point of view and gives a review of pertinent literature (LASL - GEOLOGY, LBL - GEOCHEMISTRY, LLL-GEOPHYSICS, SNL - ENERGY TRANSPORT). This report (Comparative Assessment of Five Potential Sites for Hydrothermal-Magma Systems: Energy Transport) discusses the various energy transport processes likely to be encountered in a hydrothermal-magma system. The report also reviews related literature, discusses research and field data needs, and reviews the sites from an energy transport viewpoint.

The subject of heat and mass transport within and between the hydrothermal and magma systems encompasses a wide range of possible thermal processes including: conduction, radiation, natural convection and one-and two-phase permeable convection. There are three principal thermal zones that can exist: the magma zone, the hydrothermal zone, and the intermediate, or transition, zone between the two. An additonal localized zone of critical state convection may exist in a few special situations.

Thermal sites of the type chosen for this study (Salton Trough, Rio Grande Rift, Geysers - Clear Lake Region, Long Valley, Roosevelt Hot Springs) obviously have (or had) magma of some type as the basic source of heat. In some cases, the magma body may exist as a large single cavity and in other cases it may exist as a plexus of dikes and sills. The magma body may be continuously or episodically resupplied or it may exist as a one-time intrusion of magma. Depending on the type of magma (basaltic, andesitic, rhyolitic) the magma body may have internal natural convection or it may be virtually stagnant with conduction the dominant mode of heat transfer. The magma body may be at rest in the lithosphere or it may be upmelting, and as such represent an upward moving heat source [Marsh (1978)]. In some areas the magmatic source of heat may be uncertain and the magma body may even exist at a remote lateral position from the surface thermal anomaly or site. The observed thermal anomaly and the proximate hydrothermal zone in this case can be produced by a lateral and gradual upward movement of heated groundwater from the vicinity of the magma body. The nature and position of the suspected magma body is very important in assessing the thermal processes expected at particular sites.

A hydrothermal zone may exist near the surface above or adjacent to a magma body. This zone of permeable convection may consist principally of single-phase permeable convection (liquid dominant or supercritical fluid) or two-phase permeable convection (vapor dominant). The large thermal and mass transport in many hydrothermal zones tends to mask thermal information from the deeper magma body. The temperature in areas of low permeability tends to follow the boiling curve down to depths approaching the critical point of water [Williams and McBirney (1979)]. A two-phase convection zone may change to a single-phase convection zone at greater depths when the local pressure and temperature exceed the critical point of water. There may also be cases where very low permeability and lack of groundwater inhibit the formation of a significant hydrothermal zone. In this case, conduction heat transfer may dominate all the way from the surface down to the magma body.

A third thermal zone is the intermediate or transition zone between the hydrothermal zone and the magma body. The thermal processes in this zone are largely unknown [CSDP Report (1979)]. The transition zone may be a region of porous convective brine circulation which extends down to and perhaps even into the magma [CSDP Report (1979); Norton and Knight (1977)]. Another possibiilty is that the transition zone is one where conductive heat transfer is dominant because the rock is impermeable to fluid or because of reduced heat transport that occurs when the temperature exceeds the critical temperature. In the conductive dominated case the temperature rises from the hydrothermal zone value to the ambient magma temperature and convective effects are either small or totally restricted. An example of this is the shallow magma hydrothermal model of Kilauea Iki Lava Lake [Hardee (1980)]. In such a conduction dominanted zone, the permeability and Rayleigh number are so small that permeable convection is partially or totally restricted [Cheng (1978)]. The conduction dominant temperature gradient is steep in this zone. Any water or gas in the pore space is essentially stagnant. In some cases, weak convection may occur but the mass transport can be effectively decoupled from the heat transfer process since convection does not transport enough heat to alter the temperature distribution predicted by a conduction analysis. Such a weak convective process would be difficult to measure directly, although it could be inferred from measurements of the in-situ temperature distribution and formation permeability.

An additional thermal zone which might exist in a few special situations is a zone of critical state natural convection. This can occur at significant depths in the crust (2-10 km) where the local pore pressure and temperature reach the critical pressure and temperature of water [Parmentier (1979)]. The depth where this can occur depends on the local in-situ pore pressure and the salinity of the pore water. At the critical point, natural convection heat transfer increases dramatically [Moore (1964), Dunn et al (1980)]. This is caused by large changes in the coefficient of thermal expansion, viscosity, and specific heat of fluids at the critical point which in turn results in a dramatic increase in the Rayleigh number [Rowlinson (1967), Sengers (1971)]. If the critical thermodynamic state is reached at some point above a magma body where the permeability is large enough to allow permeable natural convection, a dramatic zone of increased convection and increased heat transfer will occur at this depth. This zone would likely have a significant impact on the overall heat transfer in the magma hydrothermal system and would probably show extensive effects of dissolution and precipitation caused by the enhanced convecting circulation at the depth where the critical conditions occurred. Some observers have suggested that this is a mechanism for ore deposition [CSDP Report (1979)]. Critical convection zones may also be a preferred site for sill emplacement and may form a seismic reflection boundary.

Research Needs

Most energy transport questions relate to the insitu convective and conductive mechanisms active in the Magma-Transition - Hydrothermal Zones. While there is no shortage of models of geothermal and magma systems, there is scarcity of data from within these energy transport systems. Such data are needed to discriminate between and improve upon models that are presently based on indirect information (e.g. calculations or studies of exhumed systems). Specifically, the following typical questions are among the many of interest:

1. What factors distinguish one zone from the other? For example, is permeability a controlling factor in distinguishing the various

zones? What is the effect of fractures, dissolution (secondary porosity) and precipitation (sealing) on permeability? If convection dominates, what fluid phases exist?

2. What is the maximum depth of fluid circulation? For instance, what is the maximum depth to which downward percolating meteoric waters circulate? Do brines circulate downward to the magma surface or even into the magma?
3. What are the necessary conditions for the formation of vapor-dominant and liquid-dominant hydrothermal zones? What are the temperature - pressure - phase - chemical - characteristics of these zones? How do these zones evolve with time?
4. Does critical state permeable convection exist? Why hasn't supercritical permeable convection been observed? Is critical state permeable convection a limiting mechanism for temperatures and depths in hydrothermal circulation zones?
5. What is the nature of magma bodies? Does magma exist primarily as a localized (large liquid blob) or diffuse (plexus of dikes and sills) heat source? How is magma emplaced? Is the magma chamber isolated or resupplied? What is the state of convection in the magma chamber?

Efforts to answer these questions will require the collection and interpretation of data from deep drill holes as well as nearby shallow and intermediate depth holes. The field data will have to be synthesized and interpreted through the use of various analytical or numerical mathematical models.

Field Data

The most important set of transport data that should be collected from a deep drill hole is the following:

Temperature as a function of depth
Pore-fluid pressure as a function of depth
Fluid phase and composition as a function of depth
Nature of in-situ porosity and magnitude of in-situ permeability with depth.

These are the same measurements suggested in the CSDP report (1979). In addition, surface and downhole heat flux measurements, thermal conductivity at depth and core, and cuttings analysis are crucial measurements that should be included in this list.

Many of the geophysical and geochemical measurements will have a fundamental relationship with the thermal and mass transfer models. For instance, downhole thermal geophysical measurements and geochemical fluid measurements will yield information about the thermal character of the deeper magma body long before it is reached by a drill. Such geophysical and geochemical measurements are also, in a sense, thermal measurements.

A major unanswered question is: How much information can be gathered from a single deep drill hole? For example, even if all the data is forthcoming successfully from a single deep hole, can reasonable conclusions be drawn about the presence of convection? If in fact, data from a single deep hole should prove inadequate, is this acceptable or can a series of nearby deep holes be considered a possiblility even though the cost will increase significantly?

Data Synthesis

Considering the complexities of natural geologic systems, it is likely that field data will permit the interpretation of more than one combination of in-situ conditions. This non-uniqueness will be aggravated by our limitations to collect data from a great depth under hostile conditions. The reality of this limitation should be recognized at the outset.

The synthesis of data will be achieved through the use of mathematical models. Where the system properties are not overly complex, interpretation can be achieved through the use of analytical solutions. However, when the system becomes complex, generalized numerical methods will be required.

A variety of analytical solutions have appeared in the literature on energy transport problems related to hydrothermal and magma systems. In addition, over the past decade many numerical models have been proposed to handle energy transport in complex, three dimensional heterogeneous systems. A summary of these models is given in the following section. In comparison with the quality and quantity of data that may be forthcoming from deep drill holes, it appears that our current computational abilities far exceed the sophistication demanded by field data.

The currently available mathematical models have an important role to play in the CSDP in addition to the eventual use of the models in the interpretation of field data. This additional role will be the use of the models in the design of suitable field experiments and in the design of the instrumentation.

Brief Review of Existing Energy Transport Models

For the purpose of reviewing existing energy transport models, we have broken down these models into the categories of: magma models, hydrothermal models, and overall system models. Site-specific models tend to fall into the latter category.

Magma Models

Energy transport models for magma usually deal with ascent of magma through the asthenosphere, ascent of magma through the lithosphere, convection within the magma body, or interaction of the magma body with a hydrothermal system. A number of models have been developed for the formation of magma bodies in the asthenosphere and the ascent of these bodies through the asthenosphere and lithosphere. Although the present concern is with the state of magma bodies in the lithosphere, and particularly within the upper 10 km of the crust, models of the formation and ascent of magma are important in understanding: potential configuration of magma bodies, possibility of internal convection, and whether the magma body is resupplied or isolated. Most models of magma generation and ascent are based on the assumption of a deep heat source which produces rising diapirs or columns of molten magma [Marsh (1979), Fedotov (1975, 1976, 1979)]. Depending on local conditions, the magma may continue to rise as a plume or column [Fedotov (1975)] or the column may pinch off at the top forming an isolated rising spheroidal body of magma [Marsh (1979), Williams and McBirney (1979), Fedotov (1976), Whitehead and Luther (1975)]. Other variations on this general model exist. For instance, Turcotte and Ahern (1978) developed a porous flow model for the ascent of magma in the asthenosphere.

Once the diapiric magma body reaches the lithosphere, the magma can continue to propagate in a similar diapiric shape although the mechanism of propagation may be altered. In the asthenosphere, buoyant viscous fluid motion may be the principal mechanism of ascent whereas in the lithosphere, some other phenomenon such as melting may be significant [Yoder (1976)]. Marsh et al (1978), Marsh and Kantha (1978), and Hardee and Larson (1977) analyzed the thermal problem of magma ascent through the lithosphere by melting. Marsh concluded that the ascent velocity of a viscous sphere of magma would be greater than 10^{-7} m/s and that the magma would become superheated over much of its ascent. Hardee and Larson (1977) concluded that an upward melting magma body would be roughly equidimensional with a height-to-diameter ratio between one and five. Other models of the ascent of magma through the lithosphere have involved forced intrusion models where the flow of magma is treated as in flow through a pipe [McBirney (1959), Maaloe (1973), Marsh (1978), Hardee and Larson (1977)], ascent of magma by a corrosion cracking process [Anderson and Grew (1977)], or by an elastic crack propagation process [Weertman (1971)]. Another major but quite different theory assumes that repetitive forced intrusion of basaltic magma through a fracture network and subsequent melting of adjacent country rock is the mechanism for the generation of magma bodies in the crust [Smith (1979), Willians and McBirney (1979)]. For this theory, there is geological evidence which often shows silicic volcanism following basaltic volcanism. A number of investigators have studied convection within magma bodies and heat loss from magma bodies [Lovering (1936), Shaw (1974), Bhattacharji (1974, 1979), Carmichael et al (1976), Hardee and Larson (1977, 1980), Horai (1974, 1976), Marsh (1978), Marsh and Kantha (1978), Spera (1980)]. Smith (1979) and Eichelberger (1978) have examined petrological evidence for mixing of basalt of mantle origin with more silicic crustal material to form magma of intermediate composition and temperature. Lovering (1936) used conventional conduction solutions to study the cooling of magma bodies. Hardee and Larson (1980) and Horai (1974, 1976) used similar techniques to predict the temperature and heat flux distributions above magma bodies. Thermal radiation [Stein et al (1980)] within magma bodies has the probable first order effect of enhancing conductive heat transfer solutions. Marsh (1978) used a liquid magma sphere model to study magma cooling rates during ascent. Hardee and Larson (1977) used boundary layer and numerical techniques to study internal convection patterns and cooling rates for magma diapirs. Carmichael et al (1976) analyzed the internal magma convection problem and its effect on the composition of silicate magmatic liquids during ascent. Shaw (1974) analyzed heat and mass transfer in magma chambers using conventional Newtonian-liquid boundary layer models. Shaw also examined the effect of chemical exchange with convective boundary layers. Bhattacharji (1974, 1979) has investigated the use of scale models for natural convection studes of magmatic systems. Thermal models have also been developed for magma geometries considerably different from the ususal diapir geometry. For instance, Irvine (1970) developed heat transfer models for solidification of layered intrusions and Hess (1972) examined the thermal effects of a large intrusive magma body.

Crystallization of magmas can result in energy and mass transport. The transport can be solely local, such as a crystal growth which is a different composition than the liquid. This type of local transport and crystal growth is primarily of interest to geochemists. On a larger scale, however, crystals, may separate from the parent melt and move through the melt as a consequence of their density contrast. The role of crystal-liquid fractionation by gravitative and flow mechanisms is important because inhomogeneities in the magma system may result. These inhomogeneities may be exhibited as a sequence of zones in the magma chamber [Wager (1963), Wager and Brown (1968), McBirney and Noyes (1979)]. Such effects require explicit treatment in energy and mass transport modeling.

Hydrothermal Models

The second category of energy transport models are those that deal primarily with the hydrothermal zones above magma bodies. Hydrothermal models can be divided into those that deal with geothermal reservoirs and those models that deal with the interaction of hydrothermal fluids with magma bodies. Cheng (1978) has thoroughly surveyed heat and mass transfer models for geothermal systems. He discussed in detail: the governing equations for convective heat transfer in geothermal systems, heat transfer in hot-water geothermal systems, and heat transfer in water-steam two-phase geothermal systems. White et al (1971) developed a general model of vapor-dominated hydrothermal systems. In more specific cases, Schubert and Straus (1979) devised a one-dimensional steam-water counter-flow model for porous media for the purpose of studying two-phase flow processes in vapor-dominated geothermal systems. Rubin and Schweitzer (1972) also presented a thermal model for the phase change process in porous media. They analyzed the relative importance of conduction versus convection, the parameters affecting the temperature distribution and the interface position between the one-phase and two-phase region. Straus and Schubert (1977) performed a thermal analysis for a fluid saturated geothermal medium near the critical point and they observed that the critical Rayleigh number for the onset of convection is significantly reduced in this situation. With respect to geometrical considerations, Cheng and Lau (1974) developed a thermal model for steady convection in an unconfined geothermal reservoir. Kassoy and Zebib (1978) examined a thermal model for geothermal convection where the convection is confined to a single vertical fault or fracture and Goyal and Kassoy (1979b) studied heat and mass transfer in a saturated porous wedge.

The other general class of hydrothermal models are those that deal with the interaction of hydrothermal fluids with a pluton or magma boundary. White (1957) discussed the general interaction of hydrothermal water with magma bodies. Numerous thermal models have been developed for single phase natural convection in a permeable medium in the vicinity of a heat source. Wooding (1957, 1960, 1963), Yih (1965) and Elder (1967) examined problems of convection in saturated permeable media using analytical and experimental techniques. Straus (1974) investigated large amplitude convection in porous media. Ribando and Torrance (1976) looked at the effects of confinement, variable permeability, and thermal boundary conditions on problems involving convection in permeable media. Schrock et al (1970) ran experiments on heated cylinders in permeable media. Hardee (1976) obtained boundary layer solutions for heat transfer rates and convection rates in saturated permeable media adjacent to vertical surfaces, horizontal cylindrical surfaces and spherical surfaces. Cheng and Minkowycz (1977) also solved the thermal convection problem for a vertical plate adjacent to a permeable medium and a vertical cylinder in a permeable medium [Minkowycz and Cheng (1976)]. Parmentier (1979) obtained a solution for two-phase natural convection in a permeable medium adjacent to a heated vertical surface and he examined the geological implications of this with regard to the cooling of intrustions. Cheng and Chang (1976) obtained a solution for boundary layer flow in a saturated porous medium adjacent to a horizontal surface, and they discussed the application of this to convective flow in a liquid-dominated geothermal reservoir.

Detailed studies of the interaction of ground water with cooling igneous plutons were done by Cathles (1977) and Norton and Knight (1977). Cathles used a finite difference model of a cooling igneous intrusive to study the relation between the cooling of the intrusive and the formation of liquid and vapor dominated geothermal systems. Norton and Knight (1977) used finite difference numerical techniques to study the interaction of ground water with cooling plutons. In their calculations, the energy and momentum equations were essentially decoupled and solved for pseudo steady-state conditions. They concluded that convective effects dominate over conductive effects when the host rock permeabilities exceed 10^{-14} cm^2 (1 microdarcy). Norton and his colleagues have studied several other problems related to the interaction of ground water with magma systems.

Norton (1978) examined sourcelines and pathlines for fluids in hydrothermal systems associated with cooling plutons and Knapp and Norton (1980) used finite element methods to analyze the nature of the fracture patterns around a cooling pluton and its effects on the hydrothermal system. Norton and Cathles (1973) had earlier studied the formation of breccia pipes which result from exsolved vapor during the cooling of magma bodies.

General numerical models of the fluid thermal transport process in porous media are the basis for many current studies of hydrothermal systems, as apparent in the comprehensive bibiliography by Terra Tek [Sudol et al (1979)]. Reviews by Combarnous (1976), Cheng (1978), and Kassoy (1979), respectively, describe the recent developments in single-phase, two-phase, and site-specific models. Pinder (1979) compares and contrasts the physical and numerical aspects of several prominent geothermal codes. Recently Wang and Tsang (1980) made a detailed review of the state of the art of numerical modeling of thermohydrological flow in fractured rock masses. They reviewed the major models and discussed the governing equations, numerical methods, validation, and applications. The petroleum literature, which has been the principal forum of the finite-difference oil-gas reservoir simulators [Peaceman (1977)], now includes discussion of geothermal codes which describe transient behavior in two-dimensional [-Toronyi (1971)] and three-dimensional [Coats (1977), Thomas and Pierson (1978)] geometries. In addition to these global multidimensional simulators, there are one-dimensional radial flow simulators which describe the near-field transient response under well-test conditions [Gringarten (1978), Garg (1978), see also Intl. Well Test Symp., LBL-8883, October 1978]. Aside from the petroleum journals, there is a large body of geothermal simulation work which appears in the hydrological and geophysical journals, as exemplified by the finite-element codes of Pider (1979), Mercer (1975), Faust (1979), and Huyakorn (1978). Lying between the extremes of finite-element and finite-difference methodology, there is the integrated finite-difference approach of the two-phase SHAFT code at LBL [Narasimhan and Witherspoon (1976), Pruess et al (1979)], which has been exercised in a very wide variety of applications. A one-phase code, CCC, was also developed at LBL and has been applied to a number of geothermal applications [Lippman et al (1977), Mangold et al (1979)]. Despite the differences in the numerics of the various methods, the common physical basis is the generalized darcy-flow model which is extended to two-phase flows through the relative-permeability concept [Wooding and Moreleytoux (1976)]. Current research activities are focused on behavior of fracture-dominated media, both in single-fracture [Harlow and Parcht (1972), Goyal and Kassoy (1979a)] and in multiple-fracture [O'Neill (1978), Gringarten, Witherspoon, and Ohnishi (1975)] configurations; describing the permeability variations due to elastic deformation of the porous media [Narasimhan and Witherspoon (1977); Brownell, Garg and Pritchett (1977)]; and describing the permeability alterations due to chemical interactions between the fluid and the media. In summary, many analytical models have been used to study various hydrothermal processes, and a number of powerful computational simulators have been developed. However, there is much work yet to be done to verify their results and to validate these simulators against laboratory or field experiments.

Overall System Models

The final category of energy transport models are those models that deal with the overall hydrothermal-magma system. Many of these models are site-specific. A good discussion of general hydrothermal-magma systems is given by Elder (1976). Elder also discusses models for the hydrothermal-magma system of the Taupo area of New Zealand and the Tuscan zone in Italy. Lachenbruch and Sass (1977) have given a good discussion of broad regional heat flow models.

The lava lakes in Hawaii represent small scale versions of hydrothermal-magma systems and have been extensively studied from the thermal and mass transfer viewpoint [Peck (1978), Wright et al (1976, 1977, 1978), Richter et al (1966), Peck et al (1977), Shaw et al (1977), Hardee (1980)]. Wright et al (1977) developed a thermal model for the early time cooling of lava lakes. Shaw et al (1977) developed a numerical model of a cooling lava lake which included latent heat of crystallization and hydrothermal effects, and Peck et al (1977) applied this numerical model to the case of Alae lava lake. Hardee's (1980) thermal model for Kilauea Iki lava lake included a two-phase porous convection zone and a transition zone between the two-phase zone and the melt region. His model predictions of the temperature distribution in the crust of this lava lake and the position of the melt crust interface as a function of time agreed well with field measurements.

Many other site-specific thermal and mass transfer models have been developed. Hess (1972) produced a model for heat and mass transport in the Stillwater Igneous Complex. He determined the heat loss from the magma and accounted for the effect of settled crystals. Morgan et al (1977) made heat flow measurements at Yellowstone and suggested a thermal model for Yellowstone caldera which consisted of a large shallow magma chamber beneath a hydrothermal system. Lachenbruch et al (1976) devised a thermal conduction model for the Long Valley caldera to predict a deep magmatic system beneath the caldera. Norton and Taylor (1979) studied the Skaergaard Intrusion in Greenland and numerically simulated the cooling and crystallization of the magma and the advection process during cooling. Fedotov et al (1975) used a numerical analog method to thermally model the Avachinsky Volcano magma system and he predicted the temperature distribution above the magma body. Villas and Norton (1977) used numerical methods to study heat and mass transport processes in the Mayflower Stock System. Blackwell et al (1973) measured heat flow in the Marysville stock and developed thermal models for this area. A number of heat and mass transfer models have been constructed for various regions in the Salton Trough. Most of these models incorporate the same basic components: fluid heating at depth, percolation of the fluid through a permeable fault or fault zone, lateral spreading of the hot fluid beneath an impermeable cap rock, and subsequent conductive heat transfer through the cap to the surface [Kassoy and Goyal (1979), Black (1975), Riney et al (1979), Lau et al (1980), Bird and Elders (1975)]. An energy transport model has also been used to estimate the age of the Salton Sea Geothermal field [Younker et al (1980)].

Specific Sites

Geysers-Clear Lake Area

The thermal and mass transfer character of the Geysers-Clear Lake Area consists of a two-phase (vapor dominated) hydrothermal zone which extends downward to a shallow magma body [CSDP Report (1979), Crow (1979)]. According to White et al (1979), geophysical data [Iyer et al (in press), Young and Ward (in press), Isherwood (1976, 1977, (in press), Bufe et al (in press)] suggest that the magma body consists of a molten chamber 14 km in diameter. The magma body is thought to be as shallow as 5 km [Crow (1979), Iyer et al (1979)]. The two-phase hydrothermal zone beneath the Geysers has temperatures as high as 240°C and the zone extends to a depth of at least 3 km as evidenced by numerous drill holes down to this depth [CSDP Report (1979)]. According to White et al (1979), geochemical studies [Goff et al (1977), Thompson et al (1978)], and gravity surveys [Harrington and Verosub (in press)] indicate that hot-water convection systems with temperatures of 200C or less underlie the Clear Lake volcanic field. Also, White et al (1979) note that very high conductive heat flows and high, linear thermal gradients at the Geysers confirm the dominance of conductive heat flow between the surface and the top of the geothermal reservoir [Urban, et al (1976)]. From a transport viewpoint, the Geysers is a prime candidate for scientific drilling of a vapor-dominated geothermal/magma system [CSDP Report (1979)]. The potential shallowness of the magma body and the presence of an adjacent vapor dominant hydrothermal zone makes this site attractive. The magma body is thought to be in the Clear Lake area and does not underlie the vapor dominant hydrothermal field. A minimum of two drill holes would therefore be required to study both the vapor dominant hydrothermal field and the magma body.

Roosevelt Hot Springs

The Roosevelt Hot Springs area consists of a single-phase (liquid dominant) hydrothermal zone with a suspected shallow magma body. Geothermal well drilling indicates that the hydrothermal zone extends down to at least 2.3 km [Ward et al (1978)]. A heat flow survey in holes 40 to 200 m deep has been used to study the subsurface reservoir which appears to be 20 km² in area with temperatures near 260°C [Brook et al (1979)]. Geophysical teleseismic p-wave data [Robinson and Iyer (1979)] indicates that an igneous heat source, possibly a magma chamber, may exist at a depth of 5 km or less.

Rio Grande Rift

The Rio Grande Rift area is a large deep rift structure extending all the way from Mexico to Colorado. Known hydrothermal systems within this area are relatively small but are still relatively unexplored. The rift structure consists of deep crustal fractures, penetrating to the mantle, and in some instances there are associated magma chambers [Reiter et al (1975)]. It is these local areas with magma chambers that are the most interesting from the energy transport viewpoint.

Valles caldera is one such candidate in the rift. A partially molten magma body is thought to exist below the Valles at a depth of perhaps 5-8 km [CSDP Report (1979)]. A liquid dominated hydrothermal convection system exists beneath the Valles over an area of 130 km² with depths exceeding 2 km and temperatures generally near 260°C, but ranging to

330°C [Dondanville (1978)]. At the Hot Dry Rock site west of the caldera, the thermal gradient is about 65°C/km [Smith et al (1976), Smith (1978)]. A small vapor dominant hydrothermal system is known to exist in one part of the caldera.

There is at least one other area in the rift with a possible magma chamber. This site is at Socorro, New Mexico, where a large magma body is thought to exist at a depth of 18 km with some magma intrusions as shallow as 4-5 km [Sanford et al (1976), Chapin et al (1979)]. From the energy transport viewpoint, this site is interesting because of possible shallow basaltic magma bodies. Recent data [Reilinger et al (1980)] suggests that the Socorro magma body or related magmatic activity may extend as far north as the Belen-Albuquerque area.

Long Valley

Long Valley is a young caldera structure similar to the Valles. An extensive hot-water convection system exists with fault controlled hydrothermal activity [Stanley et al (1976), Bailey (1976)]. The depth of the hot-water hydrothermal system is not clearly defined but is probably less tham 2 km [White et al (1979)]. Geothermometer studies indicate subsurface temperatures of 200° to 250°C [Mariner and Willey (1976), Sorey and Lewis (1976), Brook and others (1979)]. Heat-flow data less than 300 m deep have been used to study the surface hydrothermal region [Lachenbruch et al (1976a)]. A generalized mathematical model of enery transport for this site was developed by Sorey et al (1978). Lachenbruch et al (1976a, 1976b) produced a heat conduction model for the caldera which indicates the presence of a deep residual magma chamber beneath the western part of the caldera. Geophysical measurements such as seismic refraction [Hill (1979)] and teleseismic techniques [Steeples and Iyer (1976)] indicate that a magma chamber exists at a depth of 7 km and extends downward to as much as 40 km depth. From an energy transport viewpoint, this site is similar to the Valles except perhaps for size and the lack of a vapor dominant hydrothermal zone.

Salton Trough

The Salton Trough is a region of oceanic rifting and transform faulting where the crust has been unusually thinned by extension . Conductive heat flows are high [Elders et al (1972)] and significant single-phase liquid-dominant hydrothermal activity exists down to depths of at least 2.5 km [Combs and Jarzabeck (1978), CSDP Report (1979)]. Five liquid-dominant convection systems have been identified with temperatures ranging from 160° to 250°C [Brook et al (1979)] and a sixth system has been suggested [Harthill (1978)]. The volcanic-related convection systems have temperatures near 350°C [Robinson et al (1976)]. The hydrothermal fluid is extremely saline (~26% in situ) [White et al (1979)]. Temperature measurements in shallow holes seldom extrapolate to deeper reservoir temperatures [Lee (1976)]. The East Mesa geothermal field has a moderate-temperature convection system (~180°C) with no surface manifestations [White et al (1979)]. The Heber geothermal field has a maximum measured temperature of 182°C [Tansev and Wasserman (1978)]. Specific magma bodies have not been located within the Salton Trough by geophysical means although molten igneous material is speculated to eixst at the base of the sedimentary section (6-7 km depth) [CSDP Report (1979)].

Conclusions

At least three major zones exist in the hydrothermal-magma system. These are: the magma zone, the hydrothermal zone, and the transition zone between the two. Most of the major energy questions relate to the nature and existence of these various zones. Of particular interest are the required conditions for the establishment of these various zones and the nature of the evolution of these zones with time. Additional energy questions concern the existence of critical state and supercritical state permeable convection in deep geothermal zones.

It is possible to rank the five sites from the viewpoint of energy transport interest (ignoring other important viewpoints such as geology, geochemistry, and geophysics). Although any ranking of this type invites criticism and controversy, the exercise is none-the-less worthwhile. A typical ranking would be:

1. Valles Caldera is a prime choice because it has liquid dominant and vapor dominant hydrothermal systems, a magma chamber and a caldera structure. The caldera structure occurs many places throughout the world and information gained from the study of one caldera structure could have application at many other locations. The Valles is also attractive because it is being studied for energy utilization [Union Oil BACA lease, Hot Dry Rock Site] and information from a deep hole could have possible application for energy utilization.
2. Geysers-Clear Lake Region is a second choice. Advantages are that this region has been well-drilled to 2 to 3 km and the region is currently used for power production. A deep

hole here could possibly provide information useful for ongoing energy utilization operations. This region is also thought to have a magma body and the region has both liquid and vapor dominant hydrothermal zones. Disadvantages are that the magma body has considerable offset from the vapor dominant hydrothermal zone which would require a larger number of holes for a complete study. Also this type of magma does not form calderas and this region is complex and somewhat unique. Information gained here would not be easily extended to many other areas.

3. Salton Trough is probably a third choice. Advantages are that the region has been studied and drilled extensively for power production. Information gained here might be useful for further power production. Disadvantages are that the region has no vapor dominant hydrothermal zone and no localized magma body to study.
4. Long Valley is probably a fourth choice. Advantages are that the site has a liquid dominant hydrothermal zone, a magma body and a caldera structure. The site is less desireable than the Valles because there is no vapor dominant zone and recent thermal gradient information [Private Communication, W. C. Isherwood, 1980] from commercial drilling activity indicates that the magma body is either cool or very deep. Commercial drilling operations have found no interesting thermal zones so far. The liquid dominant hydrothermal zone that exists appears to be strongly influenced by lateral hydrological flow. Future commercial drilling activity should be monitored at this site in case information should turn up which would make this site more interesting from the energy transport viewpoint.
5. Roosevelt Hot Springs ranks near the bottom of the list from an energy transport viewpoint. This site has no caldera, no vapor dominant zone, and the existence of a magma body is questionable. If the magma body exists it is offset laterally from the hydrothermal zone. More study is needed at this site before a deep hole could be proposed on the basis of energy transport alone.
6. Socorro ranks last from the energy transport viewpoint. It would be interesting to investigate the shallow magma intrusions. The main magma body however is very deep. An early CSDP hole for energy transport studies would be more useful in regions where the magma body is thought to exist at shallower depths.

While there is no shortage of transport models of geothermal and magma systems, there is a scarcity of data from within the heat transport system. Such data are needed to discriminate between and improve upon existing models that are presently based on indirect evidence. Interpretation of the field data will likely require the use of analytical and numerical models. An obvious conflict arises since the data is needed to verify the many theoretical and mathematical models yet the field data can probably not be synthesized and interpreted without the use of the models. Careful planning will be required to assure that the CSDP project does not generate more questions that it answers.

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